USE OF MOUNTAIN PINE BEETLE KILLED WOOD TO PRODUCE CEMENT-BONDED PARTICLEBOARD

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(Received February 2009)

Abstract. This study investigated the properties of cement-bonded particleboards made with mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins)-infected wood. Four different types of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) particles, from two different log sizes and two different years since tree death (3 and 5 yr), were considered in this study. Different formulations consisting of two cement types, two additives, various wood/cement/water ratios, and a range of additive conditions were studied. Mechanical and physical tests were conducted to examine the properties of the specimens. The results showed that wood particles from small logs (diameter < 28 cm) of 3 yr since tree death with either type of cement and calcium chloride or magnesium chloride as the additive are the best formulations. Other formulations also showed comparable mechanical and physical properties to published results of cement-bonded products. Based on the testing results, MPB woods may be used for the manufacture of the value-added wood–cement products.

Keywords: Mountain pine beetle, wood–cement composites, cement-bonded particleboard, lodgepole pine, Portland cement.

INTRODUCTION

The current mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) infestation in British Columbia, Canada, is the most destructive biotic agent of mature pine forests, principally lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), in western North America (Safranyik and Carroll 2006). During mass attack, the MPB inoculates the tree with blue-staining fungi, primarily the *Ceratocystis* species and several species of *Europhium* (Woo et al 2005). The fungi incursion weakens the tree's defense mechanisms, interrupts water translocation, and lowers wood MC, eventually leading to tree death (Byrne et al 2006). Moreover, the sapwood MC of trees drops about 100% (from 140 to 28 – 40%) from the healthy stage, and the heartwood moisture drops about 10% (35 – 25%). The volume of blue stain increases as the time increases after the beetle attack (Chow and Obermajer 2007).

From the pigmented fungi vectored by MPB, blue stain occurs in the sapwood of the attacked trees and appears in products made from stained logs, thereby affecting which products can be made and sold profitably (Byrne et al 2006; Watson 2006). Additionally, the infested trees develop splits and checks during drying, and the physical condition of wood is altered (Byrne et al 2006). It is also known that processing of the dry MPB logs may lead to the generation of more fine material and residues compared with healthy, green logs. There is a need to investigate alternative value-added wood-based products that can make use of the fine material and residues from processing MPB logs.

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One potential option is cement-bonded boards, which combine the properties of two materials: cement and fibrous materials such as wood or agricultural residues. They are panel products made up of strands, flakes, chips, particles, or fibers of wood or agricultural residues bonded with ordinary Portland cement (Eusebio 2003). Because of the good dimension stability, reduced environmental and health hazards, lower energy demands during manufacture, large sound-damping capacity, and fire resistance, these boards can be used for interior and exterior applications (Campbell and Coutts 1980; Defo et al 2004). A number of variables that influence the properties of the final product have been identified: the wood species and its physical and chemical characteristics, particle size and geometry, cement type, additives, wood/water/cement proportions, temperature, panel density, type of test, time allowed for setting, etc. (Moslemi and Pfister 1987; Jorge et al 2004). Information on some previous cement-bonded boards using various raw materials and different formulations, investigated in previous studies, is summarized in Table 1.

Many studies have shown that soluble hemicelluloses, starch, sugar, tannins, and lignin inhibit the setting of Portland cement, affecting the cure rate and ultimate strength of these cement-bonded composites (Weatherwax and Tarkow 1964; Biblis and Lo 1968; Youngquist 1999). To overcome this problem, the most common method is leaching, whereby the lignocellulosic

Table 1. *Summary of previous studies on cement-bonded particleboards with different raw materials and formulations.*

Species	Ratio[a]	Additive	Density (kg/m^3)	Bending strength (MPa)	Reference
Lodgepole pine (*Pinus contorta* Dougl.)	1:3	$CaCl_2$ 3%	1250	15.80	Moslemi and Pfister 1987
Larch (*Larix decidua* Mill.)	1:3	N/A	1210	9.54	Simatupang et al 1993
Poplar	1:2.4	$Al_2(SO_4)_3$ 1.5%	1250	5.6 10.7 15.2	Simatupang and Bröker 1998
Bamboo (*Dendrocalamus asper* Backer)	1:2.4 1:2.5	$MgCl_2$ 2.5%	1190 1170	17.41 17.88	Sulastiningsih et al 2000
Fibrous sludge	1:1.5	$CaCl_2$ 1% Na_2SiO_3 2.2% $Al_2(SO_4)_3$ 1.8%	1240	3.12	Fernandez et al 2000
Rice straw	1:1.5	$CaCl_2$ 1% Na_2SiO_3 2%	1720	7.01	Fernandez and Taja-on 2000
Chinese wingnut (*Pterocarya stenoptera* C.DC.)	1:3	$Al_2(SO_4)_3$ 4%	1200	8.79	Wei et al 2000
Korean pine (*Pinus koraiensis* Sieb.)				9.25	
Weeping willow (*Salix babylonica* Linn.)				7.25	
Mongolian oak (*Quercus mongolica* Fisch.)				8.65	
Rattan furniture waste	1:3	$CaCl_2$ 3%	1200	0.80	Olorunnisola and Adefisan 2002
CCA-treated red pine (*Pinus resinosa* Sol. ext. Ait.)	1:3	N/A	1170	9.52	Zhou and Kamdem 2002
Mixture of Eucalypt (*Eucalyptus grandis* Hill ex. Maiden) and Rubberwood (*Hevea brasiliensis* Willd ex Adr. de Juss) Müll. Arg.)	1:4	$CaCl_2 \cdot H_2O$ 4%	1220	6.40	Okino et al 2004
Maple (*Acer platanoides* L.)	1:3 1:4	$CaCl_2$ 3%	1220 1170	14.52 12.30	Papadopoulos 2007, 2008

[a] Biomaterial/cement ratio.
N/A, not applicable.

material is soaked in water 1 – 2 da to extract some of the detrimental components.

Before wood–cement production, the wood needs to be stored for at least 2 – 3 mo to reduce the moisture and sugar content (Evans 2000). However, a long storage period may cause fungal decay. The decayed wood may inhibit the setting of cement from the sugar content of the wood, resulting from enzymatic degradation of cellulose and hemicelluloses (Weatherwax and Tarkow 1964, 1967; Semple and Evans 2000). Consequently, to save storage time and cost, and to avoid inhibitory factors, the chemical components of MPB wood with lowered lignin, hemicelluloses, and concentrations of extractives content in sapwood (Woo et al 2005) may be considered as having a potential advantage in producing wood–cement composite products.

Lodgepole pine was studied as raw material where it was proven that it has relatively low inhibitory effects on cement hydration when mixed with cement (Moslemi et al 1983; Hofstrand et al 1984; Moslemi and Pfister 1987). Moreover, based on the work of Biblis and Lo (1968), it was determined that a mixture of blue-stained southern pine sapwood groundwood and cement requires a shorter setting time than an unstained groundwood mixture. This may be attributed to the fact that blue stain uses the wood starches and sugars, having a positive effect on the compatibility of wood and cement. Furthermore, Semple and Evans (2000) found that the modulus of rupture (MOR) of boards manufactured from blue-stained radiata pine sapwood was not statistically different, but still lower than that of boards made from clean sapwood.

In a previous study (Chang and Lam 2008), the compatibility between MPB-attacked lodgepole pine and Portland cement was evaluated with a hydration test, which is commonly used as a predictor of the general inhibitory properties and feasibility of the raw material before the manufacture of cement-bonded boards. The high hydration rate results showed that MPB-killed lodgepole pine may be a potential raw material for wood–cement composites as long as the mixture is treated with appropriate additives. In addition, Portland cement type III resulted in good hydration rates because of its finer structure. Because calcium chloride ($CaCl_2$) enhances crystalline formation in cement, the mechanical interlocking between the cement binder and the wood particles is increased (Moslemi et al 1983). Therefore, the use of additives can produce great improvements in the compatibility of MPB wood used in wood–cement products.

The results from a laboratory hydration test cannot be directly applied in real product processing, because different wood/cement ratios are used in laboratory test samples and in products in the marketplace. Lee et al (1987) tried different ratios and suggested that research results from mixtures with low wood/cement ratios may not apply directly to commercial processes. Moreover, some research has indicated that the hydration results may not predict the suitability for all kinds of wood species in the manufacture of wood–cement composite products (Semple et al 1999). Therefore, prototype specimens of cement-bonded particleboard with MPB wood were fabricated and the physical and mechanical properties evaluated in this work.

MATERIALS AND METHODS

Materials

In this study, four types of lodgepole pine chips, obtained from logs from the Vanderhoof area of British Columbia, were investigated. The lodgepole pine logs were small logs (diameter less than 28 cm) from 3-yr-since-death trees (3S), large logs (diameter greater than 28 cm) from 3-yr-since-death trees (3L), small logs from 5-yr-since-death trees (5S), and large logs from 5-yr-since-death trees (5L). The chips were processed in a Wiley mill with the materials passing through a 2-mm screen. The particle size distribution is shown in Fig 1.

Portland cement type I (Lehigh brand, general use Portland cement) and type III (Lehigh brand, high early strength, hydraulic cement) were used to compare the effects from the different cement types. The type I cement is typically used in the

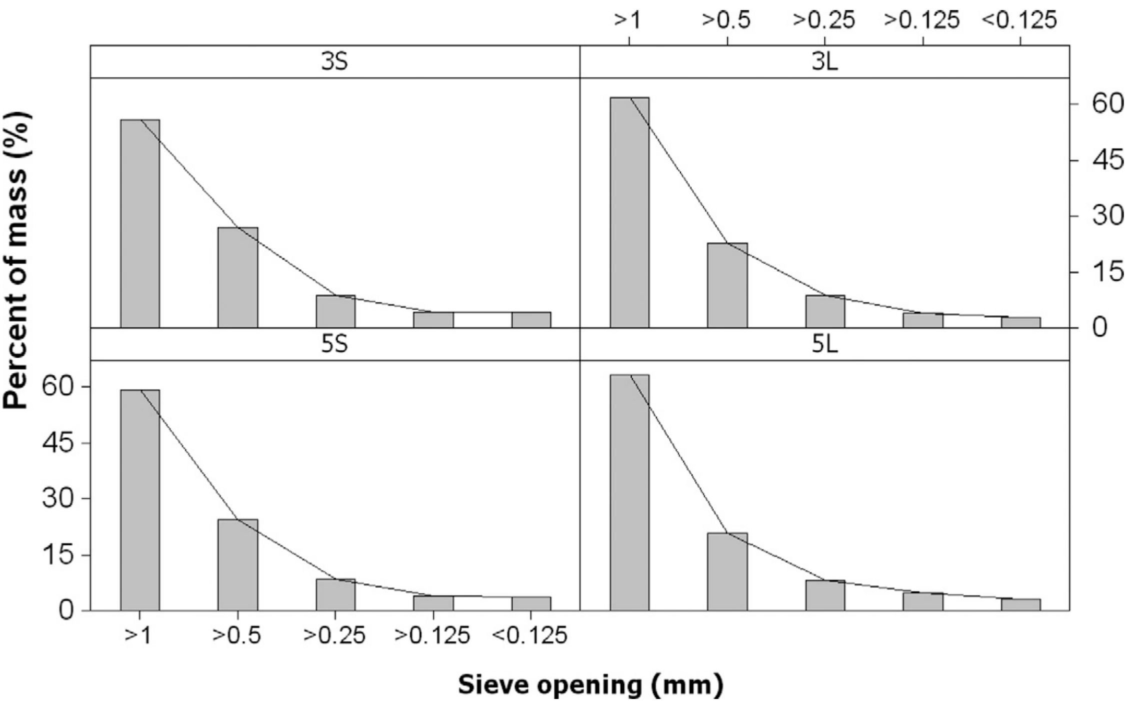

Figure 1. Particle size distribution of four types of mountain pine beetle lodgepole pine.

wood–cement industry. Type III is chemically similar to type I but is finer. This can provide more reaction surfaces for hydration to occur. In addition, two common additives, magnesium chloride ($MgCl_2$) and $CaCl_2$, were used to study the effects of different additives and contents.

Cement-bonded Particleboard Manufacturing

The boards measured 305 × 305 × 15 mm using a wood/cement ratio of 1:3 and a water/cement ratio of 0.6:1. In addition, to investigate the effects of various ratios on the mechanical properties, the formulation of 3L-typeIII-$CaCl_2$ was adopted to make the boards based on wood/cement/water ratios of 1:2:1.2, 1:3:1.8, and 1:4:2.4. The additives, which were 3% of the cement weight, were used to improve the hydration reaction of cement. Furthermore, to find the effect of the additive content on the mechanical properties of the products, 3, 5, and 8% $CaCl_2$ was added based on the dry weight of the cement with the mixture of 3S and type III Portland cement. Finally, to examine the effect of water-soaking treatment, the leaching treatment of MPB wood particles was performed for one group of samples for 24 h before fabrication.

Oven-dry wood particles (324 g) were first sprayed with about 200 mL of water, and the particles were then mixed for 2 – 3 min to facilitate an even wetting of particles. Cement powder (972 g) was then added to the particles and the remaining water (384 mL) was sprayed onto the wood–cement mixture to moisten the cement powder and ensure an even coating of particles with cement. The cement-coated particles were mixed for a further 5 min with a manual mixing tool (a handmade propeller attached to a drill). They were then removed and distributed as evenly as possible, by hand, into a 305 × 305 mm form mold to build up a mat. Four steel spacing blocks were placed at the corners to allow for a pressed final board thickness of 15 mm. The mat was pressed at ambient temperature using a hydraulically operated press. The pressed mats were kept under constant pressure for 24 h; the boards were then unclamped, stacked, and conditioned for at least 8 wk at 20 ± 1°C and 65 ± 5% RH to permit the composites to cure and increase in strength.

Experimental Plan

The considered variables included wood types (3S, 3L, 5S, and 5L), cement types (type I and type III), additive types ($CaCl_2$ and $MgCl_2$), additive content (3%, 5%, and 8%), and wood/cement/water ratios (1:2:1.2, 1:3:1.8, and 1:4:2.4). The average density of overall specimens was 1310 kg/m^3 and the coefficient of variation was 8%. The properties of bending, compression, thickness swelling, and water absorption were determined tested in accordance with ASTM D1037 (ASTM 2007). Thickness swelling was determined by:

$$T.S.(\%) = \frac{(T_f - T_i)}{T_i} \times 100 \qquad (1)$$

where T_f is the thickness (mm) of the specimen after 24 h soaking and T_i is the thickness of the specimen before soaking.
Water absorption was measured by:

$$W.A.(\%) = \frac{(W_f - W_i)}{W_i} \times 100 \qquad (2)$$

where W_f is the weight (g) of the specimen after 24 h soaking and W_i is the weight of the specimen before soaking.

The specimen for the bending test measured approximately 305 × 50 × 15 mm and the span was 270 mm. The specimen for compression measured approximately 28 × 24 × 100 mm (specimens were laminated according to the standard). In addition, the specimens for the water absorption and thickness swelling test measured approximately 150 × 150 × 15 mm with a continuous 24-h period of immersion. The MTS Sintech 30/D test machine was used to conduct the strength tests at ambient conditions. Comparisons by different factors were discussed with analysis of variance (ANOVA, $\alpha = 0.05$) to test the significant effect, and t-tests (confidence level 95%) were also conducted to test significant differences between groups. The entire experimental plan and results are summarized in Table 2, and results of ANOVA are summarized in Table 3.

Table 2. *Experimental plan and results.*

Variables	Wood	Cement type	Additive	Additive content (%)	Ratio[a]	Bending strength (MPa)[b]	SD	t-test[e]	Compression strength (MPa)[b]	SD	t-test[e]
Wood types	3S	III	$CaCl_2$	3	1:3:1.8	10.98	0.73	A	24.66	4.34	C
	3L					7.16	0.77	B	16.46	3.64	D
	5S					7.94	0.90	B	17.84	1.92	D
	5L					6.75	1.48	B	13.71	3.86	D
Cement types	5S	I	$CaCl_2$	3	1:3:1.8	8.18	1.10	A	15.65	5.43	C
		III				7.94	0.90	A	17.84	1.92	C
Additive types	3S	III	$CaCl_2$	3	1:3:1.8	10.98	0.73	A	24.66	4.34	C
			$MgCl_2$			11.54	1.24	A	28.75	3.37	C
Additive content	5L	III	$CaCl_2$	3	1:3:1.8	6.75	1.48	A	13.71	3.86	C
				5		7.51	1.15	A	15.94	2.65	C
				8		9.42	0.65	B	21.13	1.38	D
Ratio[a]	3L	III	$CaCl_2$	3	1:2:1.2	6.72	1.60	AB	13.38	2.30	C
					1:3:1.8	7.16	0.77	A	16.46	3.64	C
					1:4:2.4	5.81	0.76	B	16.43	0.99	C
Leaching treatment	5S	I	$CaCl_2$	3	1:3:1.8	8.18[c]	1.10	A	15.65[c]	5.43	C
						8.78[d]	1.27	A	19.02[d]	3.19	C

[a] Wood/cement/water ratio.
[b] Value is the average of five replicates.
[c] Without leaching treatment.
[d] With leaching treatment.
[e] For each variable, the same letter means no significant difference between groups.

RESULTS AND DISCUSSION

Thickness Swelling and Water Sorption

The results are shown in Table 4. Wood–cement composites are known to have high dimension stability when subjected to water soaking as compared with common organic-binder wood composites like plywood (Jorge et al 2004). The large variance observed in this study may be attributed to the nonuniform quality of the handmade products. Obviously, the large water absorption observed here may be a concern, but it can be explained by the trapping of free water in the defectively porous specimens. It is noted that the thickness swell is low, indicating possible low water uptake by the wood.

Effect of Different Mountain Pine Beetle Wood Types on Strength

In the bending and compression test, the MPB cement-bonded particleboard showed strengths of 6.75 – 10.98 MPa in bending and 13.71 – 24.66 MPa in compression. Referring to Table 1, MPB cement-bonded particleboards clearly showed similar strength to other comparable products.

It should be noted that the formulation with 3S (3S-typeIII-$CaCl_2$) resulted in the greatest strength in bending and compression. On the other hand, there was no significant difference among the three other types of MPB wood particles as sampled. In the previous hydration study, this formulation also showed the highest hydration rate; however, there was no significant difference among the four wood types (Chang and Lam 2008). In this work, 3S boards were fabricated first; therefore, the curing time of the boards after pressing, which was not accounted for in this work, may affect the variability in the strength of products and results as performed in the laboratory.

Effect of Cement Type on Strength

The experimental results and the statistical analysis showed that there was no significant effect of types of cement and no significant difference between two groups. However, referring to the hydration test results (Chang and Lam 2008), formulations with type III had much a quicker reaction and better hydration rate. Thus, it is reasonable to conclude that, although the finer structure of the type III cement resulted in a faster reaction than type I, this fast reaction may not improve the final strength of the product. Schwartz and Simatupang (1983) stated that type III cement exhibited greater compressive strengths after a 24-h cure period, which is at an early stage. However, after sufficient curing time, there is no significant difference from using type I because of the similar composition of two cements. Similar results were also found by

Table 3. *Results of analysis of variance test on different variables.*

Variables	Test	F-value	p value[a]
Wood types	Bending	17.80	< 0.0001**
	Compression	8.52	0.0013**
Cement types	Bending	0.14	0.7153
	Compression	0.73	0.4193
Additive types	Bending	0.74	0.4153
	Compression	2.77	0.1347
Additive content	Bending	7.21	0.0088**
	Compression	9.10	0.0039**
Ratio	Bending	1.90	0.1920
	Compression	2.42	0.1313
Leaching treatment	Bending	0.12	0.7345
	Compression	1.44	0.2650

[a] p value $> \alpha = 0.05$, not significant; ** highly significant.

Table 4. *Results of water adsorption (WA) and thickness swelling (TS) after 24 h.*

Wood type	Replicates		WA (%)	t-test[a]	TS (%)	t-test[a]
3S	4	Mean (SD)	9.70 (0.84)	A	0.23 (0.06)	C
3L	4	Mean (SD)	12.51 (6.63)	A	0.25 (0.08)	C
5S	4	Mean (SD)	10.63 (2.63)	A	0.14 (0.06)	C
5L	4	Mean (SD)	18.90 (2.38)	B	0.25 (0.02)	C

[a] The same letter means no significant difference between groups.

Moslemi and Pfister (1987). From a cost perspective, the type I cement is cheaper than type III. As to the current manufacture of wood–cement composites, type I cement is more commonly used.

Effect of Additives on Strength

The results of mechanical tests and statistical analysis indicate that the strength of boards made with $MgCl_2$ was slightly greater than, but not statistically different from, that of boards made with $CaCl_2$. Increases in the content of the additive improved the strength of products; however, sufficiently high content may be needed to have a significant effect because there is no significant difference between 3 and 5%. A higher content of additive made the hydration reaction of wood–cement mixture faster; nevertheless, it also made it difficult to work with during processing, because the mixture hardened too quickly to be distributed evenly in the mold, which may influence the final properties of the product. In addition, it was noted in other research (Sulastiningsih et al 20000; Ma et al 2000) that the value of MOR increased as the additive content increased to a specific content and then decreased as additive content increased further. This may imply that an appropriate content of additive needs to be considered carefully.

Effect of Wood/Cement/Water Ratios on Strength

Referring to the previous hydration test (Chang and Lam 2008), the wood/cement/water ratio had a significant effect on the wood–cement compatibility; the addition of wood prolonged the reaction time and decreased the hydration rate. Based on the study of Weatherwax and Tarkow (1964), increasing the wood-to-cement ratio increased the inhibitory effect on the setting of Portland cement. Furthermore, Lee and Hong (1986) and Lee et al (1987) also indicated that the density and compression strength of wood–cement mixtures were reduced as the wood/cement ratio increased.

According to the results and statistical test, there was no significant difference among the three ratios; however, the ratio 1:2:1.2 resulted in slightly lower compression strength, which coincided with the study of Lee et al (1987). Moreover, it has been mentioned in many investigations (Moslemi and Pfister 1987; Sulastiningsih et al 2000; Zhou and Kamdem 2002; Jorge et al 2004) that the wood/cement/water ratio would influence the final properties of products, although it was not observed in this study. The difference between the ratios may have been too small to see the effect on the products. In addition, the small sample size may also have affected the reliability of the statistical analysis. This variable still should be considered carefully in the manufacture of these products.

Effect of Leaching Treatment

The experimental results and statistical test showed that there was no significant difference between the group with leaching treatment and that without leaching. This may indicate that MPB wood can be applied to the manufacture of cement-bonded composites without leaching or a long period of storage time. According to this, the lower concentrations of extractives, which are inhibitory substances for cement setting in the sapwood of MPB wood, can be regarded as advantageous in producing cement-bonded boards. The benefits may be time and cost savings for the industry and improvement in production.

CONCLUSIONS

To verify the results of the hydration test from previous research and assess the feasibility of developing MPB wood–cement prototype products, cement-bonded particleboards were processed using MPB wood particles from four types of MPB-attacked logs. The results from bending and compression strength tests of MPB wood–cement boards showed comparable properties with wood–cement products in previously published studies. This indicates that MPB wood is a potential raw material for cement-bonded board manufacture.

Based on the bending and compression tests results, the formulation 3S-typeIII-$MgCl_2$ displayed the highest value; yet, when this additive was replaced by $CaCl_2$, the levels of strength were similar. On the other hand, the type of cement had no significant effect on the final properties. Although the addition of an additive improved the strength of the final MPB product, no effects from different wood/cement/water ratios were observed in this work. In addition, MPB wood–cement prototype products subjected to water soaking can be considered dimensionally stable, but the volume of water absorption was noticeable.

ACKNOWLEDGMENTS

This work was financially supported by Forestry Innovation Investment Ltd. under British Columbia's Mountain Pine Beetle Initiative: Project No. MDP-08-0066A: "Development of MPB wood plastic and wood cement products." We also express our sincere thanks to Dr. Kate Semple and Dr. Azzeddine Oudjehane, research associates in the Department of Wood Science at the University of British Columbia, for their scientific advice and review of this article.

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